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# EXPERIMENTAL STUDY OF PROPERTIES OF PERVIOUS CONCRETE USED FOR BRIDGE SUPERSTRUCTURE

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## ABSTRACT

One of the main advantages of pervious concrete is its ability to drain water easily. Moreover, earlier studies on pervious concrete have shown that it can be designed to perform well in freeze-thaw regions. Bridge superstructures placed in regions where the temperature during winter time varies around freezing point are exposed to a harsh freeze-thaw impact, since bridges are not only cooled from the topside, as a normal road bed, but also from underneath. Hence, the demands to the moisture properties of the superstructure are strict in order to ensure the necessary durability. Pearl-Chain Bridges are a new patented bridge technology consisting of a number of Super-Light Deck elements, which are post-tensioned to create an arch bridge used for example for highways. The present study investigates how pervious concrete can be applied as a stabilizing filling material between the arch substructure and the wearing course. One pervious concrete mixture containing air entrainment is designed and tested. The tests include investigations of compaction methods, compressive strength, stiffness, frost resistance and permeability.

## KEY WORDS

PERVIOUS CONCRETE, FILLING MATERIAL, PEARL-CHAIN BRIDGES, DURABILITY, FROST RESISTANCE, PERMEABILITY.

## 1. INTRODUCTION

Pervious concrete is characterized by its high void content providing it with excellent drainage properties. Generally, pervious concrete consists of Portland cement, water, coarse aggregate and in some cases admixtures improving certain properties. Moreover, it has been found that a very small amount of sand increases the strength properties (Schaefer *et al.*, 2006). However, the main idea is to avoid small fractions of aggregates and to use only well-sorted coarse aggregates by which a significant void content is established. The use of pervious concrete in Europe is still fairly limited in contrary to e.g. USA where the application of pervious concrete in road construction is much more common.

The Pearl-Chain Bridge Technology introduces a new innovative arch bridge solution challenging the traditional way of constructing highway bridges. Figure 1 shows a principle sketch of a Pearl-Chain Bridge.

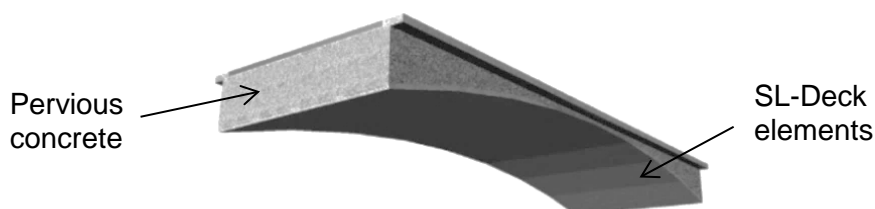


Figure 1 – Principle sketch of a Pearl-Chain Bridge

Traditionally, arch bridges are known to be statically optimal. However, the need for extensive scaffolding is a major economical drawback that explains why slab bridges are typically preferred. The Pearl-Chain Bridge Technology introduces a concept which makes it possible to reintroduce the

arch shape in highway bridging. The substructure of a Pearl-Chain Bridge is created of prefabricated Super-Light Deck elements (SL-Deck elements) which consist of a combination of light-aggregate concrete and strong concrete. Ducts are cast into the longitudinal direction of the SL-Deck elements and the Pearl-Chain arch structure is formed by collecting and post-tensioning several SL-Deck elements like pearls on a string. The post-tensioning of the SL-Deck elements is carried out next to the highway. Hereby the substructure of the Pearl-Chain Bridge is established, and afterwards it is lifted into place by use of a crane. Overall, this minimizes traffic disturbances; hence it is very much an economic favorable solution. After placement, the arch structure is stabilized by a filling material, which also supports the wearing course.

Pearl-Chain Bridges are expected to be in use for a period of 120 years, which places severe demands on the filling material in order to test and document its durability under various conditions. The filling material above the substructure is especially exposed to the harsh freeze-thaw impact occurring in mild climate countries like Denmark, where the temperature during winter times varies around freezing point. Hence, besides from meeting requirements on strength and stiffness, the filling material also needs to possess good properties regarding frost resistance in combination with good drainage properties. These requirements all together make pervious concrete an interesting opportunity for the filling material. The present study investigates the strength properties, drainage properties and freeze-thaw properties of one pervious concrete mixture.

## 2. SPECIMEN PREPARATION

### 2.1. Design of recipe

The design of the pervious concrete recipe was based on (Schaefer *et al.*, 2006) by adopting their experiences on the optimal ratio between water, binder, and aggregate found by extensive laboratory work. Three ratios have shown to be important when designing pervious concrete mixtures: the water-to-cement ratio, the binder-to-aggregate ratio and the sand-to-coarse aggregate ratio. Table 1 shows the ratios which have been adopted and applied in the present study.

Table 1 – Ratios between water, binder (cement and fly ash), and aggregates used in pervious concrete recipe. w = mass of water, c = mass of cement, b = mass of binder, a = mass of aggregates, s = mass of sand, and ca = mass of coarse aggregate

w/c	b/a	s/ca
0.29	0.23	0.093

Figure 2 shows the grain size curve for the sand and coarse aggregates used. The sand is Danish tray material and the coarse aggregate is Norwegian crushed granite.

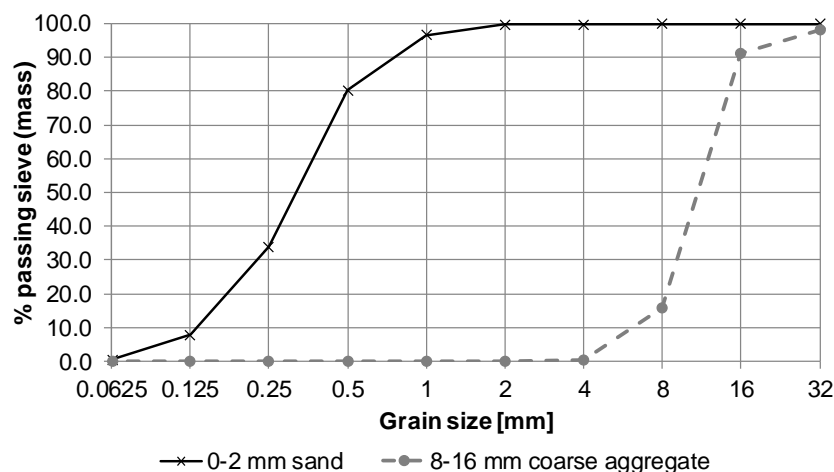


Figure 2 – Grain size distribution of sand and coarse aggregate used for pervious concrete mixture

Fly ash was used as substituent for cement such that 17% of the total amount of binder was fly ash. The cement used was CEM II/A-LL 52,5 N. Furthermore, Mapeair25 was used as air entrainment to improve the freeze-thaw properties of the pervious concrete mixture. Table 2 shows the mixture proportions.

Table 2 – Mixture proportions for 1 m<sup>3</sup> pervious concrete

<b>Cement [kg]</b>	<b>Fly ash [kg]</b>	<b>Water [kg]</b>	<b>Mapeair25 [kg]</b>	<b>Sand 0-2 mm [kg]</b>	<b>Coarse aggregate 8-16 mm [kg]</b>
340	68	105	5,3	121	1300

The mixture was designed to have a void content between the aggregates of 17.5% and a density of 1939 kg/m<sup>3</sup> as seen from Table 2. The frost resistance design of the pervious concrete was only considered from a requirement to the total amount of air in the fresh concrete to be at least 4.5%, cf. (DS 2426, 2011). The air content in the fresh concrete was measured on freshly cast pervious concrete with a Press-Ur-Meter. A Mapeair25-to-binder content of 1.3% provided 6% air content in the fresh concrete which was considered to be satisfactory.

## 2.2. Compaction and curing of specimens

Compaction of pervious concrete is one of the major challenges regarding this type of concrete. Pervious concrete is significantly vulnerable to vibrations. Too much vibration can be problematic in two ways: 1) It is difficult to control that the design void content is achieved and not exceeded and 2) There is a great risk that the cement paste runs off the aggregates and collects at the bottom of the mould. In literature several different techniques have been applied in order to control these two challenges. For the compaction method utilized in the present study, it has been chosen to avoid any vibration since it proved too difficult to control. Instead, the following procedure was applied. Specimens with a diameter of 150 mm and a height of 300 mm were cast in split moulds. The mass of pervious concrete corresponding to the volume of a mould was calculated from the density of the mixture. This mass was weighed and placed by hand in the mould, which had a special designed collar attached; see Figure 3 (left). A special designed weight of 40 kg – corresponding to a 22.6 kPa pressure – was placed on top of the pervious concrete and pushed downwards only by use of gravity until its underside was aligned with the top of the mould. In this way it was intended to achieve a void content exactly corresponding to the design value.



Figure 3 – Left: Setup used for casting specimens. Middle: Typical appearance of pervious concrete specimen. Right: Test setup for compression test with two rigid rings, each one tightly fastened with three screws to the specimen and two extensometers between the rings

The specimens cured in the moulds at room temperature for 24 h, after which they were placed in a 40°C warm water basin for 11 days to achieve an equivalent 28-days age at 20°C.

### 3. EXPERIMENTAL PROCEDURE

#### 3.1. Determination of void content

The void content was measured by the water displacement method which is based on Archimedes' principle. The mass of the cylinder was measured under water and above water after removing excess surface water. Hereby the void content,  $P$ , was calculated as:

$$P = 1 - \frac{m_0 - m_u}{V_{\text{cylinder}} \cdot \rho_w} \quad (1)$$

where  $m_0$  [kg] is the mass of the cylinder dapped by a wrung cloth above water,  $m_u$  [kg] is the mass of the submerged cylinder,  $V_{\text{cylinder}}$  [m<sup>3</sup>] is the outer volume of the cylinder, and  $\rho_w$  [kg/m<sup>3</sup>] is the density of water.

#### 3.2. Compression test setup

The compressive strength and the modulus of elasticity were determined from the same test setup on cylinders measuring D150mm/H300mm. Since pervious concrete is a relatively unknown material in Europe, no European standards exist regarding testing procedures. Hence, inspiration has been found in the standards concerning traditional concrete. This means that the compressive strength and modulus of elasticity to some extent have been determined in accordance with (DS 12390-3, 2012) and (ISO 6784, 1982). However, a main difference is that no reloading has taken place, and the modulus of elasticity is determined directly from the first loading. Figure 3 (right) shows the setup utilized with the strain measuring device installed on a pervious concrete specimen. The compression tests were carried out on a TONI 3000 kN machine at a velocity of 7 kN/s.

#### 3.3. Freeze-thaw test setup

Unlike traditional concrete, pervious concrete cannot be frost tested by applying the Borås method (SS 13 72 44, 2005) since the water bath poured on top of the concrete immediately will drain into the specimen. Hence, an alternative method has been applied inspired by (Schaefer & Kevern, 2011). The freeze-thaw tests were carried out on specimens measuring 10 cm x 10 cm x 10 cm, i.e. two cubes were cut from each cylinder; one below midsection and one above. In total four different tests were conducted as follows:

1. *Saturated method – demineralised water*: cubes freezing in demineralised water and thawing in demineralised water.
2. *Saturated method – salt water*: cubes freezing in a 3% NaCl solution and thawing in a 3% NaCl solution.
3. *Drained method – demineralised water*: cubes freezing in air and thawing in demineralised water.
4. *Drained method – salt water*: cubes freezing in air and thawing in a 3% NaCl solution.

The saturated method was included as a worst case scenario, while the drained method was included as a more realistic estimate on the actual application of pervious concrete due to its good drainage properties. The salt water was changed every 6<sup>th</sup> cycle. Freezing of the specimens took place in a cooling room at -20°C. The temperature variation was intended to follow (ASTM C666/C666M-03, 2008). However, measurements of the core temperature revealed it impossible to keep the required temperature limits within the given time intervals. Instead the temperature limits were estimated from the Borås method. Figure 4 shows these limits and the core temperature variation of the pervious concrete cubes. Due to the boundary conditions differing significantly from the Borås method it was not possible to keep the prescribed limits, especially not when freezing in air took place. As seen from Figure 4, one freeze-thaw cycle took 24 h. In the saturated method, the

boxes with the frozen specimens were during thawing placed in a water tub with 25°C heated water in order to complete one frost cycle in 24 h.

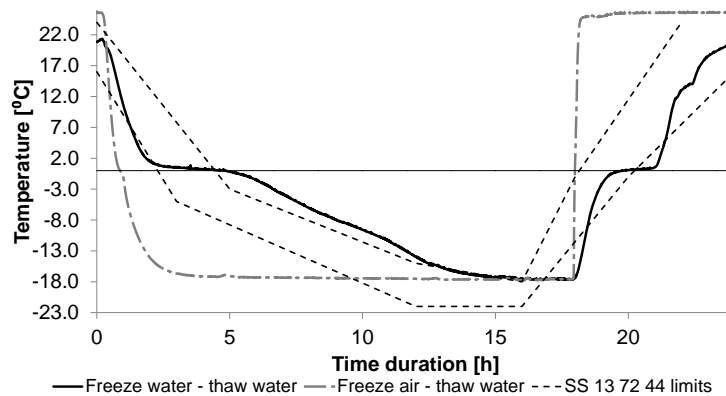


Figure 4 – Temperature variation during one freeze-thaw cycle. The core temperature has been measured at one specimen that was freezing and thawing in water and at one specimen that was freezing in air and thawing in water. Furthermore the limits from (SS 13 72 44, 2005) are shown

12 cubes were used in each of the four different tests: six cut from below midsection of the cylinder and six cut from above. Hence, in total 48 cubes were exposed to the frost test. The test was terminated after 56 frost cycles. After 24 cycles and after 56 cycles half of the cubes were tested in compression and the result was compared to the compressive strength of reference cubes. The reference cubes had not been exposed to any freezing and their compressive strength was determined when the 1<sup>st</sup> frost cycle was initiated. Moreover, the ultrasound wave speed and the mass of the specimens were measured after every 6<sup>th</sup> cycle.

### 3.4. Permeability test setup

The specimens used for the permeability test were cut from the cylinders by halving them, hereby having approximate dimensions of D150mm/H150mm. The permeability test was based on the constant head principle where a constant water height is applied on top of the specimen and the water flow is measured when steady state has been reached. Figure 5 shows the test setup. A rubber tube was mounted around a specimen and tightly fastened to the specimen by use of hose clips. Inside the rubber tube an acrylic tube was placed on top of the specimen and also tightly fastened to the rubber tube by use of hose clips.

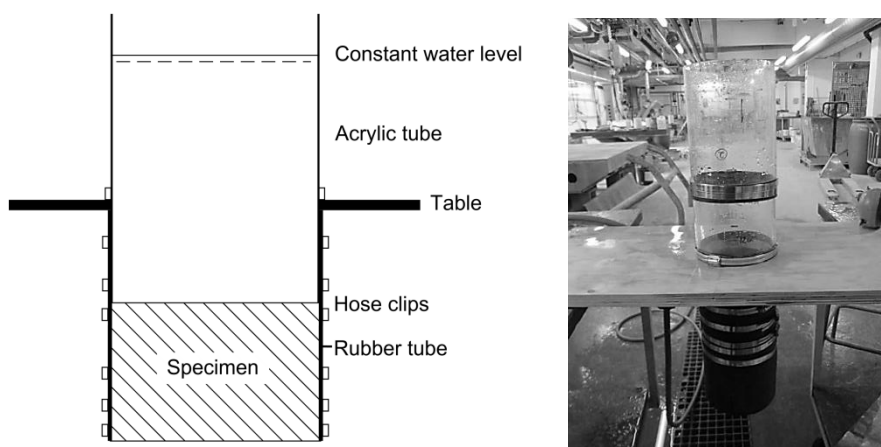


Figure 5 – Permeability test setup. Left: Principle sketch. Right: Actual setup

A water hose with a constant water flow was used to keep a constant water level. Two different water levels were examined: 12 cm and 35 cm, measured from the top of the specimen. Water was

collected in a bucket placed below the specimen for either 30 s or 120 s, dependent on whether a bottom part or a top part of the cylinder was tested. Subsequently the bucket was weighed and when three consecutively measurements were giving the same result the flow was assumed to be constant and the test was ended.

## 4. RESULTS

### 4.1 Distribution of void content

The mixture was designed to contain 17.5% voids between the aggregates. The void content of the specimens was determined after curing in accordance with Eq. (1). From 48 specimens an average void content of 17.6% was found with a standard deviation of  $\pm 1.4\%$ . From the visual inspection of the specimens it was clear that the void content was not evenly distributed throughout the specimen. As it can be seen from Figure 3 (middle) excess cement paste has a tendency to collect at the top of the specimen during compaction, which is due to the 22.6 kPa pressure not being able to reach over the entire 300 mm cylinder height. A deviation of up to 180% between the void content of the bottom and top half of the cylinder was observed. During the frost tests and permeability tests there was therefore distinguished between specimens cut from the two halves.

### 4.2. Compressive strength and stiffness of specimens

The compression tests were carried out on specimens having an equivalent 28-days age at 20°C. In total six specimens were tested in compression and in all cases the stress-strain curves were recorded. From the stress-strain curve the compressive strength  $f_c$  [MPa] was determined as:

$$f_c = \frac{N}{A} \quad (2)$$

where  $N$  [N] is the max. compressive load and  $A$  [mm<sup>2</sup>] is the cross-sectional area. The modulus of elasticity,  $E_c$  [MPa], was also determined from the stress-strain curve as:

$$E_c = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b} \quad (3)$$

where  $\sigma_a = f_c/3$  [MPa] is the upper loading stress,  $\sigma_b = 0.5$  MPa is the basic stress,  $\varepsilon_a$  is the mean strain under the upper loading stress, and  $\varepsilon_b$  is the mean strain under the basic stress.

In all compression tests it was observed that the fracture went through the cement paste in the bottom half of the specimen. Table 3 shows the compressive strength and modulus of elasticity calculated from Eq. (2) and (3) for the pervious concrete specimens.

Table 3 – Compressive strength  $f_c$  and modulus of elasticity  $E_c$

$f_c$ [MPa]	$E_c$ [GPa]
$9.9 \pm 0.8$	$16.2 \pm 5.5$

### 4.3. Frost resistance of specimens

Potential freeze-thaw damages were evaluated in three different ways. The change in ultrasound wave speed through the cubes was determined at the end of the thawing period after water had been allowed to drain off. This change was found not to vary significantly for any of the specimens.

The compressive strength was determined after 24 cycles and after 56 cycles for the cubes which had been exposed to freezing-thawing and after 0 cycles for the cubes that had not been exposed to any freezing-thawing. Equally many cubes were tested from the bottom part and from the top part of the cylinders. The evaluation of freeze-thaw damages of pervious concrete is complicated by the already big influence of the void content on the compressive strength. A direct evaluation

can only be made from cubes having the same void content. Hence, the void content of all cubes was determined from Eq. (1) before the beginning of any frost cycles. Figure 6 (left) shows the compressive strength as function of the void content for cubes exposed to saturated and drained tests in demineralised water. Figure 6 (right) shows the compressive strength as function of the void content for cubes exposed to saturated and drained tests in a 3% NaCl solution.

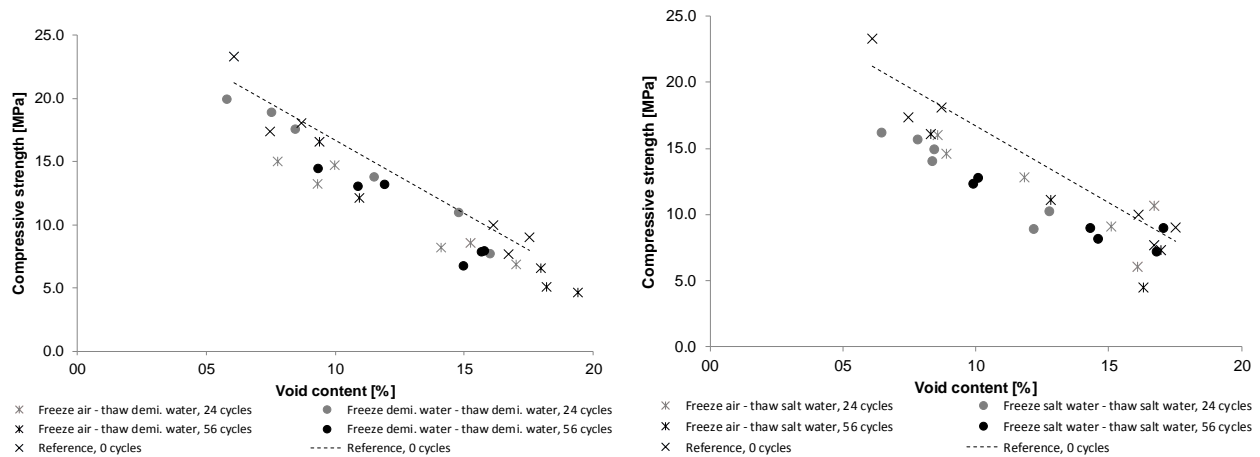


Figure 6 – Compressive strength of 10 cm x 10 cm x 10 cm cubes exposed to either 24 or 56 frost cycles as function of void content together with reference values for cubes exposed to 0 frost cycles. Left: Specimens exposed to saturated and drained test in demineralised water. Right: Specimens exposed to saturated and drained test in a 3% NaCl solution

The mass loss was determined for all cubes after every 6<sup>th</sup> cycle. In average the void content of the top cubes was 9.8% with a standard deviation of 2.2% and the void content of the bottom cubes was 15.6% with a standard deviation of 2.7%. Due to this rather small variation within each group, the mass losses of the bottom cubes have been grouped together as well as the mass losses of the top cubes. Figure 7 shows the average mass losses after 24 and 56 cycles. The result after 24 cycles is based on six cubes per test while the result after 54 cycles is based on three cubes per test.

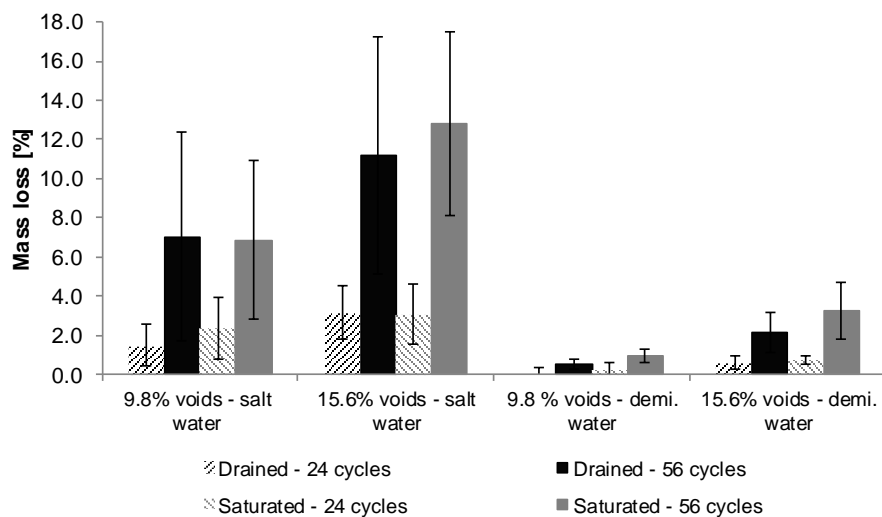


Figure 7 – Average mass loss after 24 and 56 frost cycles for 10 cm x 10 cm x 10 cm cubes exposed to saturated and drained tests in either 3% NaCl solution or demineralised water. Cubes with a void content of 9.8% and 15.6% are distinguished

The visual appearance was a strong tool in the assessment of the degradation state of the cubes. Figure 8 and Figure 9 provide examples of the appearance of two cubes at 0 cycles, 24 cycles and 56 cycles tested with and without the presence of NaCl.



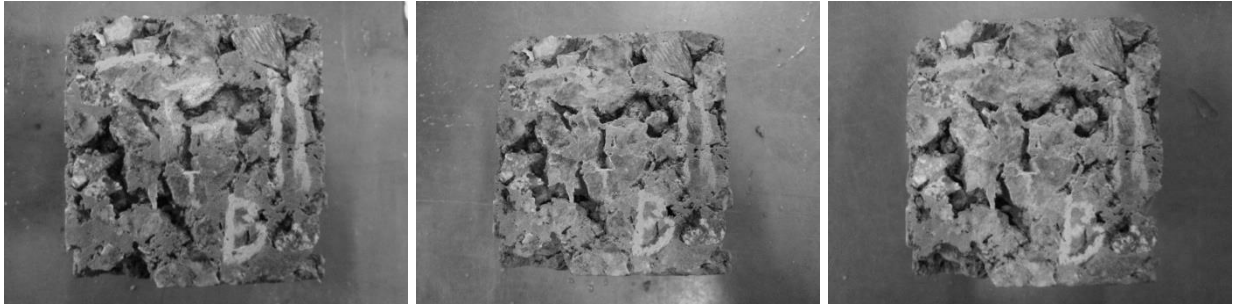


Figure 8 – Pervious concrete cube 10 cm x 10 cm x 10 cm exposed to freezing in air and thawing in demineralised water. Left: After 0 cycles. Middle: After 24 cycles. Right: After 56 cycles

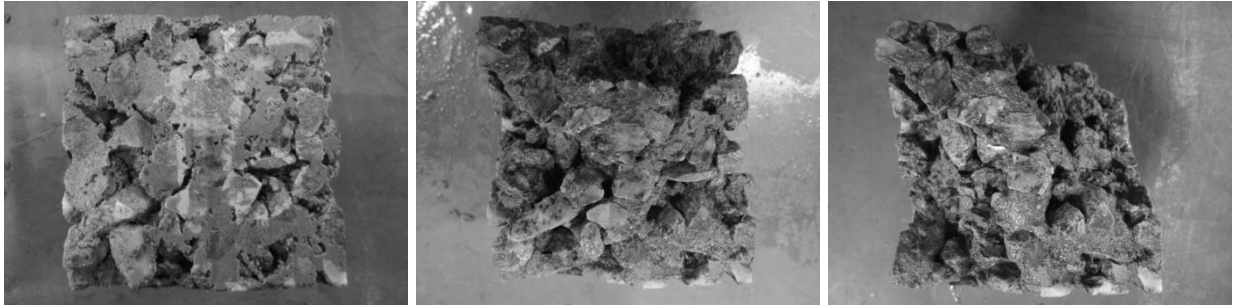


Figure 9 – Pervious concrete cube 10 cm x 10 cm x 10 cm exposed to freezing in air and thawing in a 3% NaCl solution. Left: After 0 cycles. Middle: After 24 cycles. Right: After 56 cycles

#### 4.4. Permeability of specimens

The permeability of the specimens is evaluated from the constant head principle which is based on Darcy's Law. The standard permeability coefficient at 20°C,  $k_{20}$ , is calculated as:

$$k_{20} = \frac{Q \cdot L}{A \cdot h \cdot t} \cdot \frac{\eta_T}{\eta_{20}} \quad (4)$$

where  $Q$  [ $m^3$ ] is the water flow during time  $t$  [s],  $L$  [m] is the height of the specimen,  $A$  [ $m^2$ ] is the cross-sectional area of the specimen,  $h$  [m] is the constant water level measured from the bottom of the specimen,  $\eta_T$  [ $\mu Pa/s$ ] is the water viscosity at temperature  $T$ , and  $\eta_{20}$  [ $\mu Pa/s$ ] is the water viscosity at 20°C.

Figure 10 shows the permeability coefficient as function of the void content determined from the two different water heads.

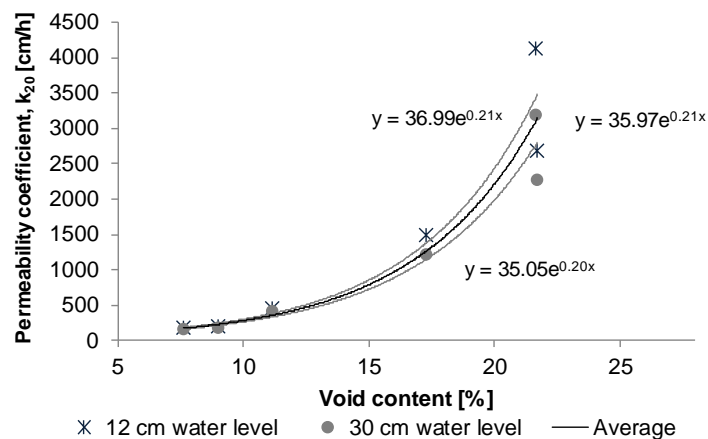


Figure 10 – Permeability coefficients as function of void content for different water heads

## 5. DISCUSSION

The strength and stiffness of the pervious concrete specimens are found to be comparable to tabulated values for traditional concrete of strength class 12 which corresponds to a compressive strength of 12 MPa and a secant E-modulus of 17 GPa. The pervious concrete mixture is found to have a compressive strength of 9.9 MPa and a stiffness of 16.2 MPa.

The difference in frost resistance between specimens being tested after the saturated method and after the drained method is seen to be unambiguous. This conclusion is based on the compression tests as well as on the mass losses. However, a distinct difference is seen between the cubes being exposed to demineralised water and the cubes being exposed to salt water. This is especially clear from the visual appearance and the mass losses of the cubes. Figure 8 and Figure 9 show the appearance of cubes exposed to demineralised water and 3% NaCl solution after 0, 24 and 56 cycles, respectively, for the drained method. Only minor fractures can be observed for the cube exposed to demineralised water, whereas big parts of the cube exposed to salt water has deteriorated already after 24 cycles. The cubes with an average void content of 9.8% in the saturated method experienced a seven times bigger mass loss when exposed to a 3% NaCl solution compared to demineralised water. For cubes with an average void content of 15.6% the corresponding mass loss was four times bigger. The results indicate that the mass loss of the cubes with an average void content of 15.6% is bigger than the mass loss of the cubes with an average void content of 9.6%, in demineralised water as well as in salt water. From Figure 7 it can be seen that the standard deviation is rather big for specimens in salt water, especially after 56 cycles. The maximum mass loss for cubes with an average void content of 15.6% in a 3% NaCl solution in the saturated method is 17.3% whereas the corresponding minimum mass loss is 8.0%. The corresponding average mass loss is 12.8% which is the most severe deterioration observed. According to (Schaefer *et al.*, 2006) a mass loss of 15% represents the terminal serviceability acceptable level. No average mass loss after 56 cycles is seen to exceed this limit. However, single results exceed this requirement.

For the cubes exposed to freezing-thawing in a salt environment, a decrease in compressive strength is clearly observed compared to the reference cubes, see Figure 6. The tendency is not as remarkable for the cubes exposed to demineralised water. For the cubes in a 3% NaCl solution the decrement is in the order of size 2-3 MPa dependent on the void content and freezing method. However, this tendency is not unambiguous, and it is not possible to distinguish between compressive strengths after 24 and 56 cycles or between saturated and drained method results.

The permeability of the pervious concrete specimens is seen to follow a strong exponential tendency with exponentially increasing permeability coefficient with increasing void content, see Figure 10. The exponential tendency was also reported in (Schaefer & Kevern, 2011). For all specimens the average permeability coefficient ranges from 177 cm/h to 2478 cm/h. Table 4 shows the permeability coefficient for common Danish soil types. As it can be seen, the permeability coefficient of the pervious concrete specimens with a void content around 10% corresponds to coarse sand. On the other hand, the permeability coefficients of the pervious concrete specimens with a void content around 22% is higher than the permeability coefficient for well-graded gravel.

Table 4 – Permeability coefficient of common Danish soil types, cf. (Ovesen *et al.*, 2007)

Soil type	Permeability coefficient [cm/h]
Gravel	1800
Coarse sand	360
Fine sand	18

A comparison of permeability coefficients of pervious concrete found in literature in USA are summarized in (Schaefer *et al.*, 2006). For pervious concrete with void contents between 15-25%, permeability coefficients between 730-1920 cm/h are reported. The permeability coefficients determined in present study for the same void contents are slightly higher.

## 6. CONCLUSION

In this paper it has been confirmed that it is possible to design a pervious concrete mixture which meets the requirements to the strength properties of a filling material used for Pearl-Chain Bridges. The pervious concrete mixture tested and investigated in present study was found to have a compressive strength of 9.9 MPa and an E-modulus of 16.2 MPa measured on cylinders with a diameter of 150 mm and a height of 300 mm. The void content was found not to be homogenous throughout the specimens with a significantly higher void content at the bottom of the specimens than at the top. This was due to the compaction method chosen. The frost resistance of pervious concrete cubes was tested by four different methods; in a saturated or drained environment during the freezing phase and with or without the presence of 3% NaCl. The change in ultrasound wave speed, change in compressive strength and mass loss was used to evaluate the degree of deterioration. The change in mass loss showed to be the best criterion for the evaluation. No clear difference was observed between the saturated and drained method. Moreover, the mass loss was seen to be depending on the void content of the cubes. However, an even stronger influence was seen by the presence of salt ions. The mass loss of cubes with an average void content of 9.8% was seven times bigger for specimens exposed to a 3% NaCl solution compared to exposure of demineralised water in the saturated environment. The most severe deterioration was observed for cubes with an average void content of 15.6% exposed to a 3% NaCl solution. After 56 cycles the average mass loss was 12.8% in a saturated environment. It is concluded that further optimization needs to take place in order to reach a satisfactory level of frost resistance if pervious concrete is to be used on Pearl-Chain Bridges as a filling material which is occasionally in contact with salt water. Finally, the permeability coefficient of the pervious concrete mixture was found to follow an exponential tendency with exponentially increasing permeability coefficient with increasing void content. For all specimens the permeability coefficient was ranging from 177 cm/h to 2478 cm/h depending on the void content of the specimens. This documented excellent drainage effect of pervious concrete with a high void content makes it highly suitable as a filling material for Pearl-Chain Bridges.

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